THE SHELL SOLAR 245 KW GRID-CONNECTED CIS THIN FILM PV ROOFTOP ARRAY: SYSTEM DESIGN AND FIRST YEAR PERFORMANCE

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ABSTRACT: Shell Solar has deployed the world's largest rooftop thin film photovoltaic system, a 245-KW array consisting of 6144 ST40 modules using Shell's innovative copper indium diselenide-based (CIS) technology. Covering nearly 3,000 square meters on its module manufacturing building, the system is arranged in 13 rows wired into 256 module strings of 24 modules each, grid-connected through a 225KW Xantrex inverter. An innovative systems design approach was employed to evaluate a new modular commercial rooftop open-rack type array support structure. Utilizing low cost light gauge cold-formed steel sections, the design minimizes roof penetrations and enables modular design for simplified installation while creating a robust structure capable of withstanding 80 mph winds and zone 4 earthquake resistant. The system is designed for flat roofs (generally defined as pitch less than 2:12, or 2 inches in 12 feet). System design is optimized by analyzing the hourly and seasonal array output with the customer's utility rate schedule. Array tilt and azimuth angles are adjusted to provide the best value proposition to the customer. Additionally, the structure is utilized in a 245 kW CIS thin film installation with the savings and performance logged on a computer via internet.
Keywords: Rooftop—1, $CuInSe_2$—2, Large Grid-connected PV systems—3

1 INTRODUCTION

The grid tied PV system market is the fastest growing segment in the PV industry. This growth has challenged the industry to approach the market differently than it has in the past. Grid tied systems are generally designed to maximize the *value* of the annual generated electrical energy as compared to *total* electrical energy generation. The best value system is realized when the methods of "systems engineering" and "value engineering" are used from manufacturing to final installation. These methods were used in the design and construction of the commercial rooftop systems to achieve the Best Value goal.

The system described herein is an "open rack" type, tilted to promote cooling and self-cleaning. Low cost light-gage galvanized steel materials are utilized to provide a modular array support structure that is easy to install. This structure is designed to adapt to most commercial flat roofs of less than 2:12 slope. The system also accommodates variations in roof heights designed for drainage while maintaining a level support structure. It is designed to be attached to the building's main framing members and easily spans up to thirty feet before attachment is required. This reduces the number of roof penetrations for the installation which lowers installed cost and improves reliability. The support rack is also designed to accept factory pre-wired, twelve-module panels, which further reduces field labor cost.

The system size was optimized by considering the structural requirements of the building, local climate conditions and the utility rate schedule.

The performance of the 245 kW PV system is presented for the Southern California Coastal region of Camarillo.

2 DESIGN PRINCIPLES

Commercial rooftops present many challenges to the solar system designer. The first consideration is the structural integrity and orientation of the building. A PV system is lightweight (< 5 lbs/sqft) but the site conditions may reveal that areas of the roof framing has already been used and cannot support additional load. In any case, a structural engineer should review the plans for the installation. In this installation, which is typical, laminated wood beams ("glu-lams") form the main support structure for the roof framing. These beams are located at 20-foot on center oriented along an east-west axis. It is desirable to directly connect the array support structure to these beams whenever possible, so that the resulting forces are then directly transmitted to the main support members.

The system size is determined by the maximum building electrical load, available roof area, location of existing rooftop equipment and project budget. To take full advantage of the available area, a tilted open rack is utilized. While flat systems appear to be an attractive design alternative because they have no row-to-row shadowing problems and provide the highest packing density, they generally cost more than racked systems, operate at higher temperatures, collect more dirt and consequently produce less annual energy than tilted arrays.

Open rack systems also allow the designer to adjust the azimuth and tilt angle for the site conditions. In addition, open rack structures can be installed over some rooftop equipment to maximize the installed system capacity and the roofing membrane is accessible for maintenance if required.

The array assembly must be analyzed for the forces due to wind and seismic conditions. These arrays are designed to accommodate up to sixteen-foot wide panels. When several of these panels are placed side by side on a 200-foot structure, they act like a sail in windy conditions. Of the forces due to wind, uplift is the predominant force subjected on the array. When located in a Seismic Zone, earthquake forces must also be considered. The ideal support structure should be designed to minimize torsion and other moments at the point of connection due to forces induced by wind and seismic events. This is known as a "pinned connection" when the structure absorbs these moments prior to the point of connection.

The support structure is attached to the building with stanchions bolted to the glu-lam beams. These stanchions must be properly flashed and sealed to achieve a quality leak free attachment. The flashing should be flexible and have a design life in excess of 30 years.

In summary, the principles used to design a "best value" grid tied PV system are:

- Determine building structural integrity through structural engineering
- Design array support structure to span the main support framing for attachment
- Open rack design to maximize system performance, allow flexibility around existing equipment and easy roof membrane access.
- Designe to local wind and seismic standards.
- Use of local climate and utility rate structure to maximize value
- Easy to install, to keep field labor at a minimum.

3 SYSTEM DESCRIPTION

The array is composed of thirteen rows or sub-arrays that vary in length depending on the rooftop conditions. Figure 1 illustrates the layout on the rooftop of the Shell Solar warehouse located in Camarillo California.

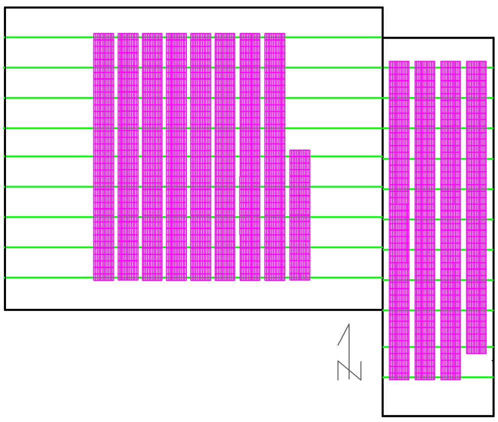

Figure 1: Rooftop layout of 245KWp CIS array in Camarillo, California. The 6144 ST40 modules are deployed in thirteen rows facing west across two adjacent roof sections

To maximize the number of modules installed, a 5-degree tilt was chosen which reduces the spacing required between adjacent rows. At higher tilt angles, (15 degrees), the necessary row spacing would require reducing the system size by approximately 60 kW due to available space.

The width of each row is 13 ft and is tilted at 5 degrees due West and has a minimum spacing between rows of 3 ft to allow access and to reduce late afternoon shadowing from one row onto another.

3.1 Mechanical design

Mechanically the system consists of 134 galvanized steel pipe stanchions attached to the main glu-lam girders at 20 feet on center and spaced 8 feet apart in the east-west direction. Attached to these stanchions are columns that telescope over the stanchion to allow for vertical height adjustment. Cross bracing at each pair of columns establishes a "pinned connection" condition at the stanchion. The columns are adjusted such that they form a 5-degree slope across the eight-foot spacing between them. Attached to these columns are galvanized cold-formed steel CEE sections (10inches x 3.25inches x 12 gauge) x 20 feet that run the length of each row. Diagonal bracing is also used along the length of each row for seismic forces. To these structures, factory pre-assembled panels are attached to form each sub-array.

3.2 Electrical design

Electrically the system is composed of 6144 Shell Solar ST40 CIS modules making this, the largest CIS-based thin film photovoltaic system in the world. Five hundred twelve factory pre-wired panels were constructed, each comprising twelve ST40 modules wired in series. Pairs of these panels were further wired in series to form 256 “source circuits”, each of 24 modules in electrical series. Every source circuit was individually fused and then all 256 were connected in parallel using 25 panel-combiner boxes. The 25 panel-combiner boxes further paralleled in 3 row-combiner boxes.

The outputs from the three row-combiner boxes were then finally fused and input into the DC disconnect feeding the Xantrex 225 kW inverter. The inverter is isolated from the buildings electrical system through a 225 kVA 208V-480V 3ph step-up transformer. A Landis & Gyr S4 revenue grade meter is used to monitor the system output between the transformer and main power distribution center.

4 PERFORMANCE

4.1 Net Metering considerations

The system was designed to maximize the value of the electrical energy produced through Net Metering from the local utility. The Net Metering agreement allows a producer of energy to be credited at the same rate charged if using electricity from the utility. For large usage customers, this rate or tariff is based on “time of use (TOU)” and the season (summer/winter). For example, the TOU rate schedule for this facility has three daily time periods and two seasons. The daily rates are “base”, “low peak” and “high peak” and are different for summer and winter. To predict the best value design for the system (maximize savings), the output from the solar system must be analyzed hourly to compare the effects of varying orientation and tilt angle of the array.

4.2 Analysis of alternate scenarios

The software used to predict the output is based on a PV array performance model introduced by David King of Sandia National Labs and adopted into the Solar Design Suite produced by Maui Solar [1]. A separate program was used to evaluate potential savings.

Table 1 summarizes the results of the analysis of two scenarios, installing the system with a tilt of 5 degrees west or 5 degrees south. The weather data used for this analysis is based on Los Angeles data. As the table indicates, the 5-degree west (azimuth 90) system produces less on an annual basis compared to the 5 degree south (azimuth 0) system, but the west facing array produces approximately 2 percent more energy during “high peak” when utility rates are highest. There are two reasons for this, first the “high peak” rate period is defined from noon to six PM and therefore the west-facing array will produce more than a southern facing array (especially during summer). The second reason is that in this coastal region of Southern California, the morning insolation profile is lower than the afternoon profile due to morning fog and overcast skies. The west-facing array produces slightly less savings as a result. This analysis compares two systems of the same size to illustrate the effect of changing azimuth. But in this circumstance, the same size system at 5 degrees south azimuth could not be installed in the same space. The south facing system would be 92% of the west facing system size.

Production	5 Deg West	5 Deg South
Base	26.6%	26.3%
Low Peak	25.54%	27.7%
High Peak	47.86%	46.0%
Annual Total	318,073kWh	325,000 kWh
Savings	$25,583	$25,825

Table I: Analysis of two installation scenarios

4.3 Actual vs. predicted performance

Array peformance modeling for the final installed design was carried out incorporating the site-specific insolation and climate factors. The predicted monthly energy delivery in kWh is charted in Figure 2. Our predictions are based on an 8% average annual soiling loss and as the dry summer months approach, the soiling losses are expected to increase in this largely agricultural area.

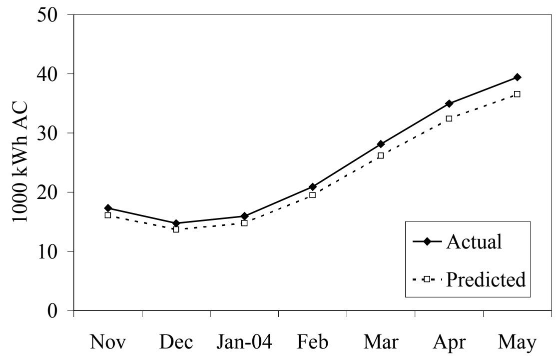

Figure 2: Predicted (□) vs. actual (♦) energy delivery from the 245KWp CIS rooftop array in Camarillo, California

Plotted on the same chart is the actual energy production for the array during the first seven months of operation. There is very close agreement between predicted and actual energy delivery, although the system is actually providing about 8% more energy than predicted.

Finally, there is also very good agreement between the predicted and actual financial performance of the system, as shown in Figure 3.

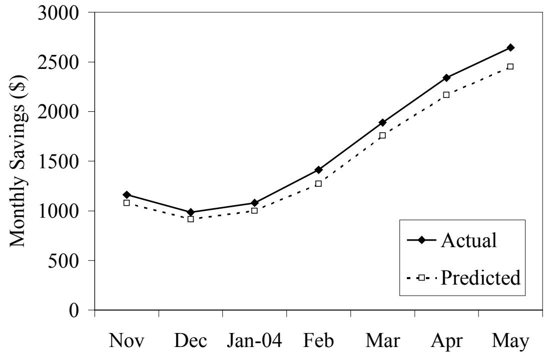

Figure 3: Predicted (□) vs. actual (♦) financial performance of the 245KWp CIS rooftop array in Camarillo, California. The actual cumulative savings of $11,513 exceeded the predicted savings of $10,642.

5 CONCLUSIONS

The modular open rack system described reduces the number of roof penetrations by spanning the buildings main support framing members using a robust light gage galvanized steel frame. The system allows for factory pre-wired panels (up to 16' x 5'4") to be installed quickly, lowering field labor costs.

The system design was maximized based on available space, utility rate schedule and local climate conditions to achieve the highest value for a grid tied Net Metered system.

To date, the system is performing better than expected by approximately 8%.

6..REFERENCES

[1] D.L. King, W.E. Boyson, and J.A. Kratochvil, Proceedings of the 29th IEEE Photovoltaic Specialists Conference (2002) 1356.